# RESEARCH MEMORANDUM

## HIGH-ALTITUDE PERFORMANCE OF AN EXPERIMENTAL TUBULAR PREVAPORIZING COMBUSTOR

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## SUMMARY

In an investigation aimed toward improving the combustion efficiency of turbojet combustors at high altitudes and high air-flow rates, an experimental tubular combustor was developed that provides for prevaporizing and premixing of the fuel with a part of the air before its introduction into the combustion zone. Combustion efficiency and total-pressure loss data are presented for three configurations selected from a total of 43 different modifications investigated. The data were obtained for a range of fuel-air ratios at inlet-air conditions simulating operation of a 5.2-pressure-ratio engine at a flight Mach number of 0.6 and at altitudes of 56,000 and 70,000 feet.

The best modification developed incorporates (1) a swirl generator for mixing the fuel and a portion of the air entering the combustor, and (2) gradual admission of additional air into the combustion zone. Maximum combustion efficiencies slightly greater than 90 percent were obtained with the best configuration at all combustor-inlet conditions tested. Use of gaseous fuel (propane) did not generally increase combustion efficiencies over those obtained with liquid fuel, indicating that factors other than vaporization rate were limiting maximum combustion efficiencies obtainable with this combustor.

Combustion efficiencies obtained with the best experimental combustor were appreciably higher, in the low fuel-air ratio range, than those obtained with a production-model combustor of the same diameter; at high fuel-air ratios the differences were small. Total-pressure losses of the best prevaporizing combustor were somewhat greater than those of the reference production-model combustor. Low-altitude performance of the experimental combustor was not investigated; thus, little is known regarding its durability or carbon-deposition characteristics.

## INTRODUCTION

Improvement in the combustion efficiency of turbojet-engine combustors at low pressures and high air-flow rates is the objective of a research program being conducted at the NACA Lewis laboratory. As a part of this research, a number of design principles relating to the fuel-air environment of the primary combustion zone have been investigated. The object of the investigation reported herein was to evaluate the merits of a combustor design that provides for prevaporizing and premixing of the fuel with air before its introduction into the combustion zone. 3461

Design criteria for optimum combustion efficiency performance can be established through investigations of the various factors controlling the fuel-air environment of the combustion zone. Thus, the optimum manner of introducing primary air into the combustion zone has been studied extensively (e.g., ref. 1). Improvements in liquid-fuel distribution, such as through fuel staging, have increased combustion efficiencies of both tubular and annular combustors (refs. 2 and 3), especially at high fuel-air ratios and high air-flow rates. In addition, prevaporization of the fuel (ref. 1) and control of the primary fuel-air ratio, as well as combinations of the two (ref. 4), have improved combustor performance.

In the present investigation, a combustor was developed that utilizes a prevaporization technique somewhat similar to that used in reference 4. Liquid fuel is injected into the primary-air stream ahead of the dome of the combustor liner. The resultant mixture then impinges on the upstream surface of the combustor dome which is exposed to flame on the downstream side. Independent control of primary- and secondary-air flows is not incorporated into this design; proportioning of the air depends upon the passage areas.

Forty-three different design modifications were investigated. However, since most of the individual changes affected the performance of the combustor only slightly, three modifications, each representing major design features, were selected for presentation in this report. The investigation was conducted in a direct-connect duct with a 7-inch-diameter tubular combustor; MIL-F-5624A, grade JP-4, fuel was used. Combustor inlet-air conditions simulating reduced throttle operation of a 5.2-pressure-ratio engine at a flight Mach number of 0.6 and at altitudes of 56,000 and 70,000 feet were investigated.

Performance factors investigated were combustion efficiency, operating range, and combustor pressure losses. A comparison is made between the performance of the best configuration operating with liquid and with gaseous fuels (propane) in order to indicate the effectiveness of the prevaporizor. In addition, the performance of the best modification is compared with that of a production-model tubular combustor (ref. 5) of equivalent size.

# APPARATUS

## Test Installation

The combustor test facility is shown schematically in figure 1. Combustor-inlet and -outlet ducts were connected to the laboratory air-supply and low-pressure-exhaust facilities, respectively. Air-flow rates and combustor pressures were regulated by remotely controlled valves located upstream and downstream of the combustor. The combustor-inlet air was preheated to the desired temperature by electric air heaters.

## Instrumentation

Air flows were metered by concentric-hole, sharp-edged orifices installed according to A.S.M.E. specifications. Liquid and gaseous fuel flows were measured by calibrated rotameters and calibrated sharp-edged orifices, respectively. The location and arrangement of the inlet-air and exhaust-gas instrumentation planes are shown in figure 1. Inlet-air and exhaust-gas total pressures were determined by two six-point total-pressure rakes at stations A-A and D-D (fig. 1), respectively. Inlet-air and exhaust-gas total temperatures were measured by two bare-wire, single-junction iron-constantan thermocouples at station B-B and by eight single-shielded, two-point chromel-alumel thermocouple rakes at station C-C, respectively. The exhaust-gas thermocouples were connected in a parallel circuit; by means of a suitable switching arrangement, either individual measurements or an average measurement of the 16 thermocouples could be obtained.

## Combustors

The investigation was conducted with tubular combustors with 7.0-inch-diameter outer shells and $5\frac{5}{8}$-inch-diameter inner liners. Sketches of three combustor configurations used are shown in figure 2. The combustor liner was 20 inches long, and the distance from the apex of the dome or flame holder to the plane of the exhaust-gas thermocouples was 28 inches. The fuel injector was located $5\frac{1}{4}$ inches upstream of the apex of the dome.

The primary or combustion air for the experimental combustors flowed through a 3-inch-diameter pipe; fuel was sprayed into this air stream from a 15.3-gallon-per-hour hollow-cone spray nozzle in a downstream direction (fig. 2). The resultant mixture of fuel and air impinged on the cone-shaped dome or flame holder at the upstream end of the combustor and then entered the combustion chamber through an annular passage between the liner and the dome. A spark plug ignited the mixture (fig. 2). Secondary or dilution air entered the combustor through four $3\frac{1}{2}$- by 1-inch-wide rectangular slots located at the downstream end of the combustor.

Design variables that were investigated related primarily to the way in which the fuel-air mixture was introduced into the combustion zone. They included (1) size of annulus between dome and liner, (2) shape of dome, (3) shape and number of reversing scoops used to direct a portion of the mixture into the sheltered region behind the flame holder, (4) length and location of truncated-cone baffle used to direct the mixture toward the center of the combustor, and (5) location and size of combustion-air entry holes. A total of 43 design modifications were tested during the investigation. The combustor configurations shown in figure 2 were selected for discussion in this report, because they represented the major design features investigated; they include the best configuration developed in the investigation. The distinctive features of these configurations are as follows:

3461

<u>Configuration I</u>. - This combustor (fig. 2(a)) utilized complete separation of primary and dilution air; thus, all the combustion air was premixed with the fuel.

<u>Configuration II</u>. - In this combustor (fig. 2(b)) 24 holes of 5/8-inch diameter were drilled in the liner in order to provide a gradual admission of additional combustion air. At the same time, the minimum diameter of the truncated-cone baffle was increased, and the downstream lips of the reversing scoops of configuration I were cut off to direct the fuel-air mixture away from the dome and thus to prevent excessive cooling of the dome surface by the unburned mixture.

<u>Configuration III</u>. - In this combustor (fig. 2(c)) the reversing scoops and truncated-cone baffle were replaced by a swirl generator in an effort to increase the mixing action in the wake of the dome. The number and location of the air-entry holes were the same as in configuration II. A cutaway view of configuration III is shown in figure 3.

## Fuel

The liquid fuel used in this investigation was MIL-F-5624A, grade JP-4. Physical properties of the fuel are presented in table I. The gaseous fuel was commercial propane.

## PROCEDURE

Combustion efficiency, total-pressure loss, and temperature distribution data were obtained with the three experimental combustors over a range of fuel-air ratios at each of the following test conditions:

3461

| Condition | Combustor-inlet total pressure, in. Hg abs | Combustor-inlet total temperature, °F | Air-flow rate per unit combustor area[a], lb/(sec)(sq ft) | Simulated flight altitude at 85-percent rated engine speed, ft |
|---|---|---|---|---|
| A | 15 | 268 | 2.78 | 56,000 |
| B | 8 | 268 | 1.49 | 70,000 |
| C | 15 | 268 | 2.14 | 56,000 |
| D | 15 | 268 | 3.62 | 56,000 |

[a]Based on maximum cross-sectional area of combustor housing (0.267 sq ft).

These conditions simulate inlet-air conditions encountered in a 5.2-pressure-ratio turbojet engine operating at 85-percent rated speed at a flight Mach number of 0.6 at the altitudes listed. Air-flow rates at conditions A and B are representative of current turbojet engines, while those at conditions C and D are approximately 23 percent less and 30 percent greater than those used in current engines, respectively.

Combustion efficiency was computed as the ratio of actual enthalpy rise across the combustor to the enthalpy supplied by the fuel, according to the method described in reference 6.

Combustor reference velocities were computed from the air mass-flow rates, the combustor-inlet density, and the maximum combustor cross-sectional area. The total-pressure loss is expressed as the dimensionless ratio $\Delta P/q_r$, where $\Delta P$ is the combustor total-pressure drop and $q_r$ is the reference velocity pressure based on the velocity and density of the combustor-inlet air at the reference plane.

The radial temperature distribution at the combustor outlet was determined at all test conditions for two values of combustor temperature rise (680° and 1180° F). In addition, combustor lean and rich blow-out limits were recorded whenever they were encountered within the range of fuel-air ratios investigated.

## RESULTS AND DISCUSSION

### Combustor Development

The object of the investigation reported herein was to evaluate the merits of a combustor design principle that provides for prevaporizing and premixing of the fuel with a part of the air before its introduction into the combustion zone. In order to develop a combustor that gives high combustion efficiencies, 43 different modifications were investigated, most of which were aimed at increasing (1) the rate of fuel vaporization by promoting higher temperatures on the vaporizing surfaces and (2) the rate of mixing of fuel and air with a minimum loss in pressure. Since most of the individual changes affected the performance of the combustor only slightly, three configurations representing significant design changes were selected for presentation in this report. Performance data for these three configurations are presented in table II.



<u>Configuration I</u>. - In configuration I (fig. 2(a)) all the primary air was introduced with the fuel. The quantity of air introduced in this way was approximately 25 percent of the total air flow to the combustor, based on relative areas, but was not controlled independently. Combustion efficiencies obtained with this configuration at the four inlet-air conditions are shown in figure 4. In general, combustion efficiency varied between approximately 70 and 90 percent at conditions A, C, and D (56,000 feet altitude) and between approximately 54 and 67 percent at condition B (70,000 feet altitude). The performance of this combustor was very limited at low fuel-air ratios. At conditions A, C, and D, combustor blow-out or rapidly decreasing efficiencies occurred at fuel-air ratios slightly less than 0.01. At condition B, combustor blow-out occurred at a fuel-air ratio slightly less than 0.016.

These results indicate that the primary-zone fuel-air ratio was too lean for optimum performance because of either insufficient fuel vaporization or excessive amounts of primary air. The temperature of the upstream face of the dome, as indicated by an iron-constantan thermocouple welded to the dome, was quite low, generally less than the combustor-inlet temperature. This was an indication that the dome was not very effective in vaporizing the liquid fuel impinging on it. Although enrichment of the primary zone by reducing the amount of primary air introduced would be expected to improve the lean-end performance of this combustor, figure 4 shows that at high fuel-air ratios combustion efficiencies decreased, indicating that a reduction in primary air would seriously reduce combustion efficiencies in this region. Furthermore, since at high fuel-air ratios surging combustion and burning at the secondary-air slots was encountered with this configuration, further reduction in primary air did not seem warranted.

Configuration II. - In configuration II a series of holes was added to the liner (fig. 2(b)) to provide a more gradual admission of primary air. The downstream lips of the reversing scoops were cut off, which allowed the gases to be directed away from the dome. In addition, the truncated-cone baffle was shortened somewhat in order to reduce the constricting effect of the baffle and thus to induce more reverse flow into the primary zone. Because a number of intermediate changes in the shape and surface details of the dome, designed to increase the heat-transfer rate through the dome, produced no noticeable improvement in combustor performance, the dome of configuration I was retained for configuration II.

Combustion efficiencies obtained with configuration II (fig. 5) were generally higher than those obtained with configuration I, varying between approximately 82 and 90 percent at conditions A, C, and D. Also, at these conditions the range of operable fuel-air ratios was extended appreciably in the lean region. At condition B, combustion efficiency decreased from approximately 93 to 72 percent as fuel-air ratio was increased from 0.012 to 0.026, indicating some over-enrichment of the fuel-air mixture in the primary zone at this condition.

Combustion was generally stable, and no surging was encountered. Furthermore, dome surface temperatures were appreciably higher with this combustor than with configuration I, indicating that the modifications of the reversing scoops were effective in reducing the scrubbing action on the downstream surface of the dome.

Configuration III. - Further modifications were made on configuration II in an effort to increase the over-all level of combustion efficiencies obtainable. Configuration III incorporated a swirl generator at the upstream end of the combustor (fig. 2(c)). This swirl generator, which replaced the truncated-cone baffle and the reversing scoops, was expected to increase the rate of mixing and the intensity of reverse flow in the primary-combustion zone. The results obtained with this combustor are shown in figure 6. Combustion efficiencies were slightly higher than those obtained with configuration II, maximum efficiencies slightly greater than 90 percent being obtained at all conditions. Dome surface temperatures were somewhat higher than with configuration II, a fact which may have contributed to the somewhat better performance of configuration III. In general, modification III performed satisfactorily; no rough combustion was observed over the entire range of conditions covered.

## Comparison of Liquid and Gaseous Fuel

It had been observed that dome surface temperature generally decreased with increasing fuel flow, from values as high as 800° F at low fuel-air ratios to values less than inlet-air temperature at high fuel-air ratios. These data indicate that, at high fuel-air ratios, the fuel was not completely vaporized at the dome surface. In order to determine the effectiveness of the prevaporizer, the performance of configuration III was determined with gaseous propane as well as with liquid JP-4 fuel.

Comparison of the performance of configuration III with liquid and with gaseous fuel (fig. 7) shows that, in general, combustion efficiencies obtained with propane were no higher than those obtained with liquid fuel. These results indicate either that the fuel was completely prevaporized and other factors were limiting the maximum performance of this combustor or that complete prevaporization of the fuel was not essential. The fact that, with liquid fuel dome surface temperatures decreased with increasing fuel-air ratio while with propane they remained fairly constant may be taken as an indication that prevaporization of the fuel was not complete at all fuel-air ratios. 3461

## Combustor Total-Pressure Losses

Combustor total-pressure losses of configuration III are presented in figure 8, where the ratio of total-pressure drop to the reference dynamic pressure $\Delta P/q_r$ is plotted against combustor-inlet to -outlet gas-density ratio. Pressure drop ratio $\Delta P/q_r$ increased from a value of approximately 17 at isothermal conditions to a value of 23 at a density ratio of 3.2 for conditions A, C, and D. At the low-pressure condition B, the pressure drop was somewhat higher, as has been observed previously (e.g., ref. 1). For comparison, the isothermal $\Delta P/q_r$ values for configurations I and II were 17.6 and 15.2, respectively. The dashed line in figure 8 represents the pressure drop of a tubular production-model combustor of the same diameter. The total-pressure losses of the production-model combustor are somewhat lower than those of configuration III.

## Combustor-Outlet Temperature Distribution

Combustor-outlet temperature profiles were recorded at two values of temperature rise (680° and 1180° F) wherever possible. The secondary combustion zone was provided with large rectangular slots (fig. 2) for the purpose of obtaining a uniform temperature profile. As a result, individual combustor-outlet temperatures were generally within ±200° F of the mean temperature. No effort was made to improve further temperature distribution, even though in some cases, probably because of misalinement of parts, individual temperatures varied by more than 200° F from the mean.

## Evaluation of Experimental Prevaporizing Combustors

The combustion efficiencies obtained with configurations I to III are presented in figures 4 to 6, which indicate that configuration III produced the highest combustion efficiencies of all the models selected. Maximum combustion efficiencies slightly greater than 90 percent were obtained at all test conditions. In figure 9, combustion efficiencies obtained with configuration III are compared with those of a tubular production-model combustor (ref. 5) of the same diameter. At the low fuel-air ratios, configuration III produced considerably higher combustion efficiencies than the production-model combustor. At high fuel-air ratios, the performance of the two combustors was about the same. However, it should be noted that the production-model combustor was designed on the basis of other factors not considered in the present investigation, such as low-altitude operation, starting, durability, and carbon-deposition characteristics. Furthermore, previous experiments have shown that similar improvement in the low fuel-air-ratio range performance of the production-model combustor can be obtained by relatively simple modifications, such as installation of fuel dams to prevent fuel wash along the liner walls (ref. 5). Thus, the dashed line in figure 9 shows combustion efficiencies obtained with the reference production-model combustor equipped with fuel dams (data from ref. 5). There is very little difference between the performance of the modified production-model combustor and that of the experimental prevaporizing combustor described herein.

In reference 4 an experimental combustor was developed with design objectives similar to those described herein. In the combustor of reference 4, the major portion of the fuel was prevaporized on the external surfaces of the primary-combustion zone and premixed with air before entering the primary zone. The remainder of the fuel was injected, as a liquid spray, directly into the combustion zone for starting and piloting purposes. In general, combustion efficiencies of the best configuration from reference 4 were slightly higher than those of configuration III. The slight improvement in performance might be attributed to the larger diameter of the combustor of reference 4. It has been observed (ref. 1) that increases in the hydraulic radius of combustors tend to increase their combustion efficiencies.

Thus, the results obtained in this investigation indicate that fuel prevaporization and premixing can be utilized to produce high combustion efficiencies, but that, if high performance over a wide range of fuel-air ratios is desired, gradual admission of combustion air rather than complete premixing appears to be preferable. Furthermore, the results obtained here and in other investigations (e.g., ref. 1) indicate that other design factors, such as combustor size, limit maximum combustor performance.

## CONCLUDING REMARKS

In an investigation designed to evaluate the merits of a combustor design principle that provides for prevaporizing and premixing of the fuel with air before its introduction into the combustion zone, an experimental prevaporizing combustor was developed which produced maximum combustion efficiencies slightly greater than 90 percent at all test conditions. Although the performance of this combustor was appreciably better at low fuel-air ratios than that of a production-model combustor of the same size, experience has shown that similar improvements in the 3461
performance of the production-model combustor can be obtained by other, simpler means. Furthermore, since the experimental combustor was designed for high-altitude operation only, design changes would probably be necessary in order to provide satisfactory operation over the entire range of flight conditions normally encountered.

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Cleveland, Ohio, September 10, 1954

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TABLE I. - FUEL ANALYSIS

| Fuel properties | MIL-F-5624A, grade JP-4 (NACA fuel 52-53) |
|---|---|
| A.S.T.M. distillation D86-46, °F | |
| Initial boiling point | 136 |
| Percent evaporated | |
| 5 | 183 |
| 10 | 200 |
| 20 | 225 |
| 30 | 244 |
| 40 | 263 |
| 50 | 278 |
| 60 | 301 |
| 70 | 321 |
| 80 | 347 |
| 90 | 400 |
| Final boiling point | 498 |
| Residue, percent | 1.2 |
| Loss, percent | 0.7 |
| Aromatics, percent by volume | |
| A.S.T.M. D-875-46T | 8.5 |
| Silica gel | 10.7 |
| Specific gravity | 0.757 |
| Viscosity, centistokes at 100° F | 0.762 |
| Reid vapor pressure, lb/sq in. | 2.9 |
| Hydrogen-carbon ratio | 0.170 |
| Net heat of combustion, Btu/lb | 18,700 |

TABLE II. - PERFORMANCE DATA OF SELECTED EXPERIMENTAL COMBUSTORS

| Run | Combustor-inlet total pressure, in. Hg abs | Combustor-inlet total temperature, °R | Air-flow rate, lb/sec | Air-flow rate per unit area, lb/(sec)(sq ft) | Combustor reference velocity, ft/sec | Fuel-flow rate, lb/hr | Fuel-nozzle pressure drop, lb/sq in. | Fuel-air ratio | Mean combustor-outlet temperature, °R | Mean temperature rise through combustor, °F | Combustion efficiency, percent | Total-pressure drop through combustor, in. Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration I; fuel, MIL-F-5624A, grade JP-4 | | | | | | | | | | | | |
| 1 | 15.0 | 728 | 0.571 | 2.139 | 78.13 | ---- | --- | ------- | ---- | --- | ---- | 0.6471 |
| 2 | 15.0 | 728 | .572 | 2.142 | 78.29 | 24.5 | 7.0 | 0.01190 | 1470 | 742 | 87.0 | .8162 |
| 3 | 15.0 | 728 | .572 | 2.142 | 78.29 | 20.8 | 7.0 | .01010 | 1390 | 662 | 90.8 | .7869 |
| 4 | 15.0 | 731 | .572 | 2.142 | 78.61 | 33.3 | 11.0 | .01617 | 1660 | 929 | 82.0 | .8824 |
| 5 | 15.0 | 728 | .572 | 2.142 | 78.29 | 38.7 | 14.0 | .01880 | 1790 | 1062 | 81.7 | .9358 |
| 6 | 15.0 | 728 | .572 | 2.142 | 78.29 | 42.5 | 17.0 | .02064 | 1940 | 1212 | 86.1 | 1.104 |
| 7 | 15.0 | 728 | .572 | 2.142 | 78.29 | 49.0 | 24.0 | .02380 | 2090 | 1362 | 85.3 | 1.178 |
| 8 | 15.0 | 730 | .572 | 2.142 | 78.50 | 55.2 | 32.0 | .02681 | 2185 | 1455 | 82.0 | 1.029 |
| 9 | 15.0 | 728 | .742 | 2.779 | 101.8 | 24.2 | 8.0 | .00906 | 1290 | 562 | 85.0 | 1.279 |
| 10 | 15.1 | 730 | .742 | 2.779 | 101.2 | 35.0 | 13.0 | .01310 | 1518 | 785 | 84.1 | 1.353 |
| 11 | 15.0 | 729 | .742 | 2.779 | 101.7 | 43.7 | 19.0 | .01638 | 1688 | 956 | 83.8 | 1.419 |
| 12 | 15.1 | 728 | .742 | 2.779 | 100.9 | 51.6 | 27.0 | .01852 | 1835 | 1107 | 83.2 | 1.478 |
| 13 | 15.0 | 730 | .742 | 2.779 | 101.8 | 59.2 | 36.0 | .02216 | 2020 | 1290 | 86.1 | 1.946 |
| 14 | 15.0 | 730 | .742 | 2.779 | 101.8 | 66.5 | 44.0 | .02482 | 2080 | 1350 | 81.2 | 1.765 |
| 15 | 15.0 | 728 | .969 | 3.629 | 132.6 | 41.1 | 17.0 | .01178 | 1460 | 732 | 86.6 | 2.346 |
| 16 | 15.0 | 728 | .969 | 3.629 | 132.6 | 36.0 | 14.0 | .01052 | 1360 | 632 | 84.5 | 2.257 |
| 17 | 15.0 | 728 | .969 | 3.629 | 132.6 | 31.5 | 10.0 | .00903 | 1200 | 472 | 71.3 | 2.184 |
| 18 | 15.0 | 728 | .969 | 3.629 | 132.6 | 48.0 | 22.0 | .01376 | 1550 | 822 | 84.1 | 2.419 |
| 19 | 15.0 | 728 | .969 | 3.629 | 132.6 | 58.4 | 31.0 | .01617 | 1660 | 932 | 82.2 | 2.507 |
| 20 | 15.0 | 728 | .969 | 3.629 | 132.6 | 66.6 | 47.0 | .01967 | 1785 | 1067 | 78.0 | 2.574 |
| 21 | 15.0 | 728 | .969 | 3.629 | 132.6 | 74.0 | 56.0 | .02122 | 1840 | 1112 | 76.5 | 2.684 |
| 22 | 8.0 | 728 | .397 | 1.487 | 101.9 | 22.9 | 6.5 | .01603 | 1440 | 712 | 62.6 | .8235 |
| 23 | 8.0 | 728 | .397 | 1.487 | 101.9 | 21.9 | --- | .01553 | 1410 | 682 | 62.5 | ------ |
| 24 | 8.0 | 728 | .397 | 1.487 | 101.9 | 35.5 | 10.5 | .02344 | 1780 | 1062 | 66.4 | .9191 |
| 25 | 8.0 | 728 | .397 | 1.487 | 101.9 | 35.4 | 10.5 | .02477 | 1790 | 1062 | 63.0 | .9118 |
| 26 | 8.0 | 728 | .397 | 1.487 | 101.9 | 30.0 | 10.6 | .02099 | 1680 | 952 | 65.6 | .9118 |
| 27 | 8.0 | 728 | .397 | 1.487 | 101.9 | 41.6 | 11.5 | .02911 | 1830 | 1102 | 56.4 | .9191 |
| 28 | 8.0 | 728 | .397 | 1.487 | 101.9 | 44.1 | 11.5 | .03086 | 1850 | 1122 | 54.5 | .9118 |
| Configuration II; fuel, MIL-F-5624A, grade JP-4 | | | | | | | | | | | | |
| 29 | 15.0 | 728 | 0.570 | 2.135 | 78.01 | ---- | ---- | ------- | ---- | ---- | ---- | 0.5598 |
| 30 | 8.0 | 728 | .400 | 1.498 | 102.6 | ---- | ---- | ------- | ---- | ---- | ---- | .5513 |
| 31 | 15.0 | 728 | .570 | 2.135 | 78.01 | 19.9 | ---- | 0.00970 | 1325 | 597 | 84.6 | .6785 |
| 32 | 15.0 | 728 | .570 | 2.135 | 78.01 | 18.0 | ---- | .00977 | 1295 | 567 | 88.5 | .6818 |
| 33 | 15.0 | 728 | .570 | 2.135 | 78.01 | 26.9 | 7.0 | .01311 | 1520 | 792 | 84.8 | .6985 |
| 34 | 15.0 | 728 | .570 | 2.135 | 78.01 | 32.0 | 9.0 | .01559 | 1660 | 932 | 85.2 | .7206 |
| 35 | 15.0 | 728 | .570 | 2.135 | 78.01 | 37.8 | 14.0 | .01842 | 1800 | 1072 | 84.2 | .7574 |
| 36 | 15.0 | 728 | .570 | 2.135 | 78.01 | 43.0 | 19.0 | .02096 | 1920 | 1192 | 83.4 | .7868 |
| 37 | 15.0 | 728 | .570 | 2.135 | 78.01 | 50.8 | 26.0 | .02478 | 2090 | 1362 | 82.2 | .8258 |
| 38 | 15.0 | 728 | .747 | 2.798 | 102.2 | 22.1 | ---- | .00822 | 1250 | 522 | 86.6 | 1.088 |
| 39 | 15.0 | 728 | .745 | 2.790 | 102.0 | 28.3 | 8.0 | .01055 | 1410 | 682 | 89.5 | 1.126 |
| 40 | 15.0 | 728 | .745 | 2.790 | 102.0 | 38.1 | 14.0 | .01421 | 1610 | 882 | 87.8 | 1.184 |
| 41 | 15.0 | 728 | .745 | 2.790 | 102.0 | 45.9 | 22.0 | .01711 | 1760 | 1032 | 86.7 | 1.243 |
| 42 | 15.0 | 728 | .743 | 2.783 | 101.7 | 54.8 | 33.0 | .02049 | 1930 | 1202 | 85.9 | 1.338 |
| 43 | 15.0 | 728 | .743 | 2.783 | 101.7 | 65.0 | 47.0 | .02430 | 2110 | 1382 | 85.0 | 1.378 |
| 44 | 15.0 | 728 | .965 | 3.614 | 132.1 | 29.0 | 8.0 | .00835 | 1230 | 502 | 82.0 | 1.860 |
| 45 | 15.0 | 728 | .965 | 3.614 | 132.1 | 37.1 | 12.0 | .01088 | 1405 | 677 | 87.8 | 1.918 |
| 46 | 15.0 | 728 | .965 | 3.614 | 132.1 | 45.9 | 22.0 | .01321 | 1560 | 832 | 88.3 | 2.029 |
| 47 | 15.0 | 728 | .965 | 3.614 | 132.1 | 56.0 | 37.0 | .01670 | 1750 | 1022 | 87.9 | 2.116 |
| 48 | 15.0 | 728 | .965 | 3.614 | 132.1 | 71.1 | 57.0 | .02047 | 1910 | 1182 | 84.5 | 2.279 |
| 49 | 15.0 | 728 | .965 | 3.614 | 132.1 | 82.8 | 79.0 | .02383 | 2040 | 1312 | 81.8 | 2.324 |
| 50 | 8.0 | 728 | .400 | 1.498 | 102.6 | 26.9 | ---- | .01868 | 1755 | 1027 | 79.4 | .7279 |
| 51 | 8.0 | 728 | .400 | 1.498 | 102.6 | 22.1 | ---- | .01535 | 1620 | 892 | 82.6 | .6858 |
| 52 | 8.0 | 728 | .400 | 1.498 | 102.6 | 19.9 | ---- | .01382 | 1550 | 822 | 85.8 | .6765 |
| 53 | 8.0 | 728 | .400 | 1.498 | 102.6 | 17.7 | ---- | .01229 | 1530 | 802 | 91.4 | .6691 |
| 54 | 8.0 | 728 | .400 | 1.498 | 102.6 | 17.0 | ---- | .01181 | 1520 | 792 | 93.8 | .6618 |
| 55 | 8.0 | 728 | .400 | 1.498 | 102.6 | 29.4 | ---- | .02042 | 1810 | 1082 | 77.1 | .7279 |
| 56 | 8.0 | 728 | .400 | 1.498 | 102.6 | 33.4 | ---- | .02319 | 1890 | 1162 | 75.6 | .7427 |
| 57 | 8.0 | 728 | .400 | 1.498 | 102.6 | 36.9 | 12.5 | .02563 | 1980 | 1252 | 72.7 | .7574 |

TABLE II. - Concluded. PERFORMANCE DATA OF SELECTED EXPERIMENTAL COMBUSTORS

| Run | Combustor-inlet total pressure, in. Hg abs | Combustor-inlet total temperature, °R | Air-flow rate, lb/sec | Air-flow rate per unit area, lb/(sec)(sq ft) | Combustor reference velocity, ft/sec | Fuel-flow rate, lb/hr | Fuel-nozzle pressure drop, lb/sq in. | Fuel-air ratio | Mean combustor-outlet temperature, °R | Mean temperature rise through combustor, °F | Combustion efficiency, percent | Total-pressure drop through combustor, in. Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration III; fuel, MIL-F-5624A, grade JP-4 | | | | | | | | | | | | |
| 58 | 15.0 | 728 | 0.570 | 2.135 | 78.01 | ---- | ---- | ------- | ---- | ---- | ---- | 0.6176 |
| 59 | 15.0 | 728 | .570 | 2.135 | 78.01 | 18.1 | ---- | 0.00882 | 1330 | 602 | 93.6 | .7152 |
| 60 | 15.0 | 728 | .571 | 2.139 | 78.16 | 25.1 | ---- | .01124 | 1460 | 732 | 90.6 | .7279 |
| 61 | 15.0 | 728 | .573 | 2.146 | 78.42 | 26.9 | 8 | .01401 | 1605 | 877 | 88.5 | .7647 |
| 62 | 15.0 | 728 | .575 | 2.146 | 78.42 | 35.2 | 12 | .01706 | 1760 | 1032 | 87.0 | .8015 |
| 63 | 15.0 | 728 | .575 | 2.146 | 78.42 | 41.8 | 18 | .02026 | 1920 | 1192 | 86.1 | .8456 |
| 64 | 15.0 | 728 | .573 | 2.146 | 78.42 | 51.0 | 29 | .02472 | 2125 | 1397 | 84.6 | .8897 |
| 65 | 15.0 | 728 | .744 | 2.787 | 101.8 | 20.5 | ---- | .00766 | 1200 | 472 | 85.8 | 1.147 |
| 66 | 15.0 | 728 | .744 | 2.787 | 101.8 | 27.3 | 7 | .01019 | 1400 | 672 | 91.2 | 1.191 |
| 67 | 15.0 | 728 | .744 | 2.787 | 101.8 | 35.8 | 12 | .01337 | 1585 | 857 | 90.4 | 1.250 |
| 68 | 15.0 | 728 | .744 | 2.787 | 101.8 | 44.1 | 20 | .01647 | 1760 | 1032 | 90.0 | 1.338 |
| 69 | 15.0 | 728 | .744 | 2.787 | 101.8 | 52.9 | 30 | .01975 | 1926 | 1197 | 88.6 | 1.397 |
| 70 | 15.0 | 728 | .744 | 2.787 | 101.8 | 62.0 | 43 | .02315 | 2085 | 1357 | 87.2 | 1.471 |
| 71 | 15.0 | 728 | .964 | 3.610 | 131.9 | 29.9 | 9 | .00853 | 1235 | 507 | 83.0 | 1.893 |
| 72 | 15.0 | 728 | .964 | 3.610 | 131.9 | 36.9 | 14 | .01063 | 1420 | 692 | 90.2 | 2.125 |
| 73 | 15.0 | 728 | .964 | 3.610 | 131.9 | 45.0 | 21 | .01297 | 1570 | 842 | 91.4 | 2.205 |
| 74 | 15.0 | 728 | .966 | 3.618 | 132.2 | 58.9 | 36 | .01636 | 1760 | 1032 | 90.8 | 2.309 |
| 75 | 15.0 | 728 | .966 | 3.618 | 132.2 | 68.0 | 52 | .01955 | 1910 | 1182 | 88.2 | 2.412 |
| 76 | 15.0 | 728 | .966 | 3.618 | 132.2 | 80.5 | 75 | .02315 | 2020 | 1292 | 82.8 | 2.574 |
| 77 | 15.0 | 728 | .966 | 3.618 | 132.2 | 85.7 | 85 | .02464 | 2060 | 1332 | 80.8 | 2.647 |
| 78 | 8.0 | 728 | .396 | 1.483 | 101.6 | 18.5 | ---- | .01297 | 1580 | 852 | 92.5 | .7353 |
| 79 | 8.0 | 728 | .396 | 1.483 | 101.6 | 23.0 | ---- | .01613 | 1695 | 967 | 85.7 | .7574 |
| 80 | 8.0 | 728 | .396 | 1.483 | 101.6 | 27.0 | ---- | .01893 | 1780 | 1052 | 80.4 | .7794 |
| 81 | 8.0 | 728 | .398 | 1.483 | 101.6 | 33.1 | 10.5 | .02321 | 1910 | 1182 | 75.1 | .8088 |
| 82 | 8.0 | 728 | .398 | 1.483 | 101.6 | 34.8 | 12.5 | .02440 | 1930 | 1202 | 73.0 | .8235 |
| Configuration III; fuel, gaseous propane | | | | | | | | | | | | |
| 83 | 15.0 | 728 | 0.967 | 3.622 | 132.3 | 26.4 | ---- | 0.00759 | 1230 | 502 | 84.8 | 2.007 |
| 84 | 15.0 | 728 | .967 | 3.622 | 132.3 | 23.4 | ---- | .00673 | 1095 | 367 | 89.3 | 1.985 |
| 85 | 15.0 | 728 | .967 | 3.622 | 132.3 | 31.7 | ---- | .00910 | 1375 | 647 | 92.3 | 2.103 |
| 86 | 15.0 | 728 | .967 | 3.622 | 132.3 | 42.3 | ---- | .01216 | 1560 | 832 | 90.8 | 2.206 |
| 87 | 15.0 | 728 | .967 | 3.622 | 132.3 | 52.6 | ---- | .01511 | 1740 | 1012 | 90.4 | 2.316 |
| 88 | 15.0 | 728 | .967 | 3.622 | 132.3 | 63.9 | ---- | .01835 | 1915 | 1187 | 89.0 | 2.515 |
| 89 | 15.0 | 728 | .967 | 3.622 | 132.3 | 77.2 | ---- | .02217 | 2040 | 1312 | 82.9 | 2.598 |
| 90 | 15.0 | 728 | .967 | 3.622 | 132.3 | 81.4 | ---- | .02337 | 1880 | 1152 | 67.4 | 2.574 |
| 91 | 15.0 | 728 | .742 | 2.779 | 101.6 | 19.3 | ---- | .00725 | 1220 | 492 | 87.1 | 1.147 |
| 92 | 15.0 | 728 | .742 | 2.779 | 101.6 | 28.0 | ---- | .01048 | 1455 | 727 | 90.8 | 1.213 |
| 93 | 15.0 | 728 | .742 | 2.779 | 101.6 | 35.4 | ---- | .01324 | 1630 | 902 | 90.9 | 1.272 |
| 94 | 15.0 | 728 | .742 | 2.779 | 101.6 | 41.5 | ---- | .01554 | 1760 | 1032 | 89.9 | 1.309 |
| 95 | 15.0 | 728 | .742 | 2.779 | 101.6 | 49.3 | ---- | .01845 | 1915 | 1187 | 88.6 | 1.368 |
| 96 | 15.0 | 728 | .742 | 2.779 | 101.6 | 63.5 | ---- | .02377 | 2170 | 1442 | 86.0 | 1.581 |
| 97 | 15.0 | 728 | .572 | 2.142 | 78.29 | 18.9 | ---- | .00917 | 1385 | 657 | 93.1 | .7206 |
| 98 | 15.0 | 728 | .572 | 2.142 | 78.29 | 25.7 | ---- | .01245 | 1570 | 842 | 89.7 | .7721 |
| 99 | 15.0 | 728 | .572 | 2.142 | 78.29 | 33.6 | ---- | .01631 | 1770 | 1042 | 86.7 | .7941 |
| 100 | 15.0 | 728 | .572 | 2.142 | 78.29 | 39.7 | ---- | .01928 | 1920 | 1192 | 85.3 | .8582 |
| 101 | 15.0 | 728 | .572 | 2.142 | 78.29 | 49.6 | ---- | .02407 | 2150 | 1422 | 83.7 | .9338 |
| 102 | 15.0 | 728 | .572 | 2.142 | 78.29 | 13.6 | ---- | .00658 | 1130 | 402 | 77.6 | .6765 |
| 103 | 15.0 | 728 | .572 | 2.142 | 78.29 | 19.3 | ---- | .00939 | 1370 | 642 | 88.9 | .7059 |
| 104 | 15.0 | 728 | .572 | 2.142 | 78.29 | 25.3 | ---- | .01229 | 1550 | 822 | 88.7 | .7574 |
| 105 | 15.0 | 728 | .572 | 2.142 | 78.29 | 37.0 | ---- | .01799 | 1840 | 1112 | 84.6 | .8088 |
| 106 | 8.0 | 728 | .397 | 1.487 | 101.9 | 11.1 | ---- | .00776 | 1215 | 487 | 80.5 | .6544 |
| 107 | 8.0 | 728 | .397 | 1.487 | 101.9 | 13.8 | ---- | .00962 | 1370 | 642 | 86.8 | .6838 |
| 108 | 8.0 | 728 | .397 | 1.487 | 101.9 | 18.8 | ---- | .01316 | 1560 | 832 | 83.9 | .7132 |
| 109 | 8.0 | 728 | .397 | 1.487 | 101.9 | 25.5 | ---- | .01787 | 1785 | 1057 | 80.7 | .7721 |
| 110 | 8.0 | 728 | .397 | 1.487 | 101.9 | 29.2 | ---- | .02043 | 1880 | 1182 | 78.5 | .8309 |
| 111 | 8.0 | 728 | .397 | 1.487 | 101.9 | 31.7 | ---- | .02218 | 1740 | 1012 | 62.9 | .8603 |
| 112 | 8.0 | 728 | .397 | 1.487 | 101.9 | 10.0 | ---- | .00700 | 1010 | 282 | 51.1 | .6177 |

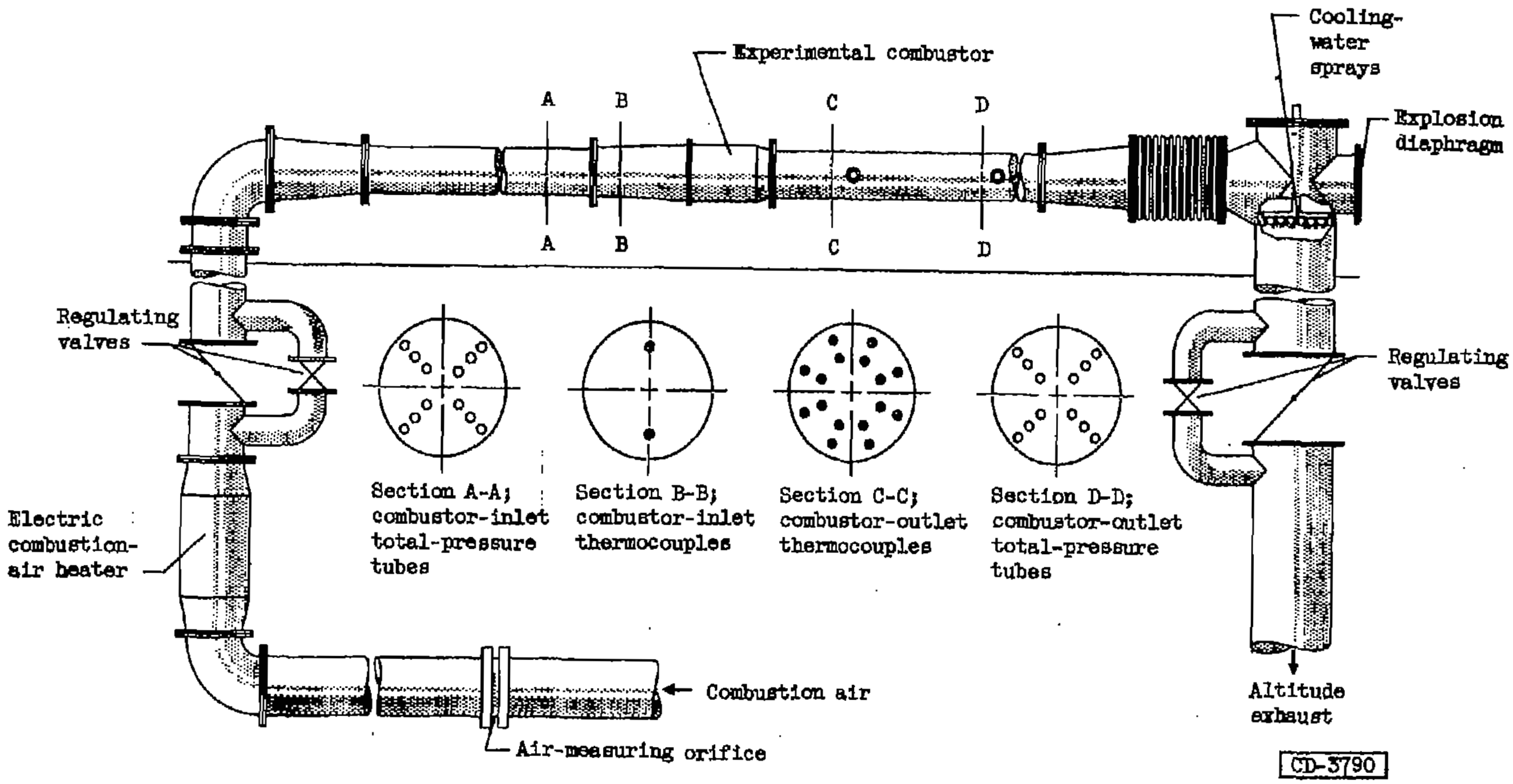


Figure 1. - Experimental-combustor installation, showing inlet and outlet ducting and instrumentation stations.

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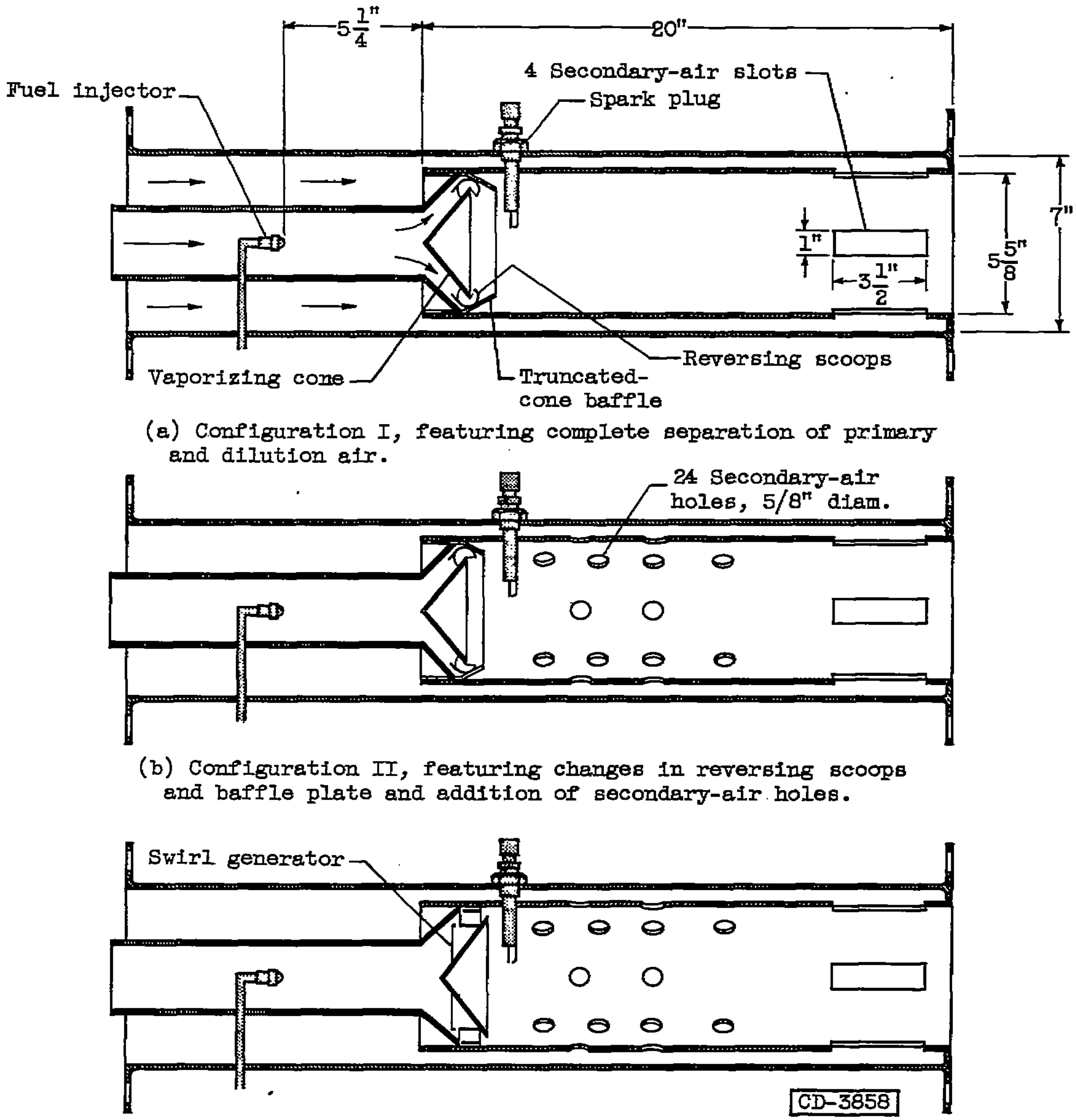


(a) Configuration I, featuring complete separation of primary and dilution air.

(b) Configuration II, featuring changes in reversing scoops and baffle plate and addition of secondary-air holes.

(c) Configuration III, featuring swirl generator.

Figure 2. - Sketches of experimental prevaporizing combustors.

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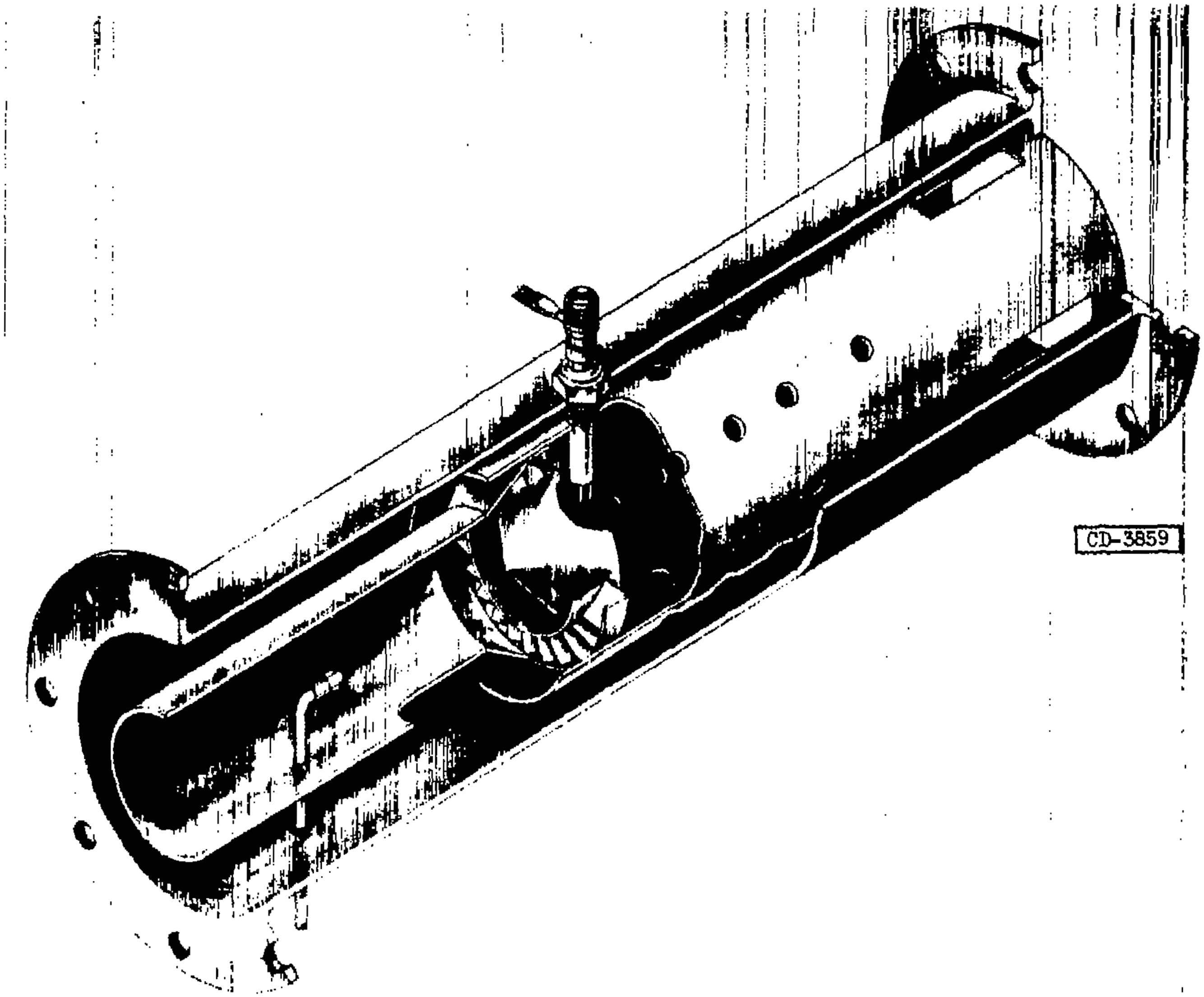
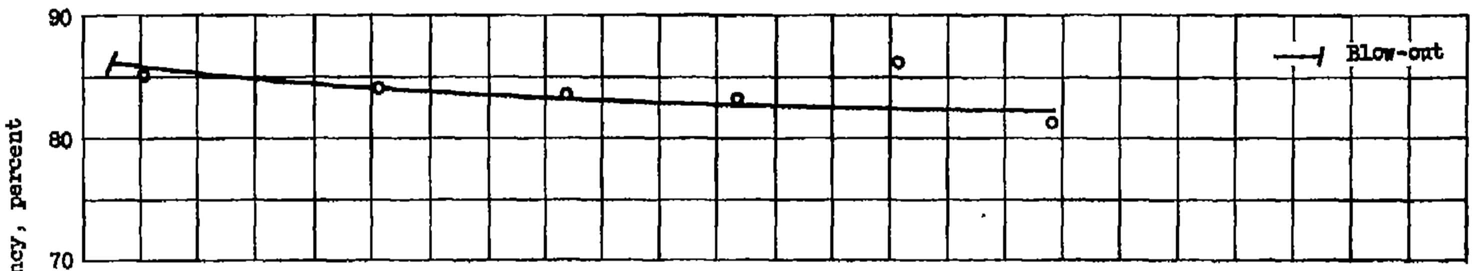
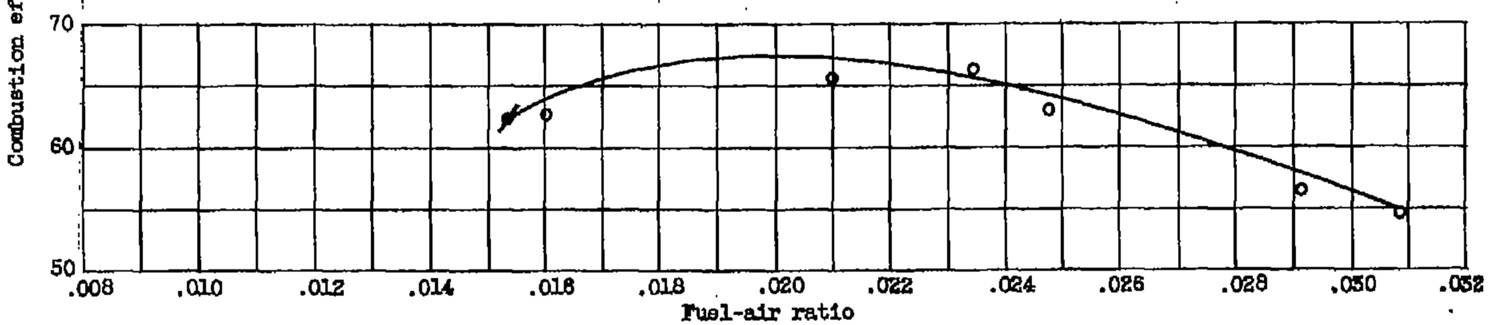



Figure 3. - Cutaway view of configuration III.

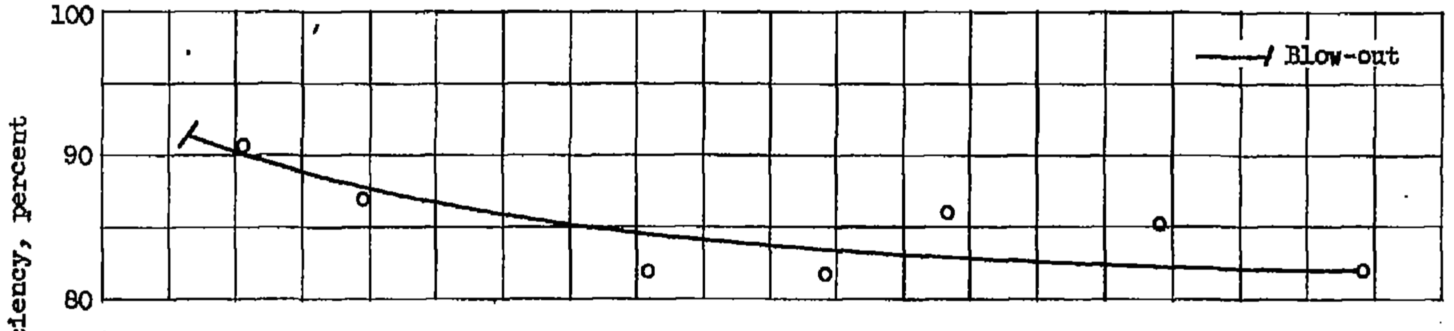



(a) Condition A. Air-flow rate, 2.78 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

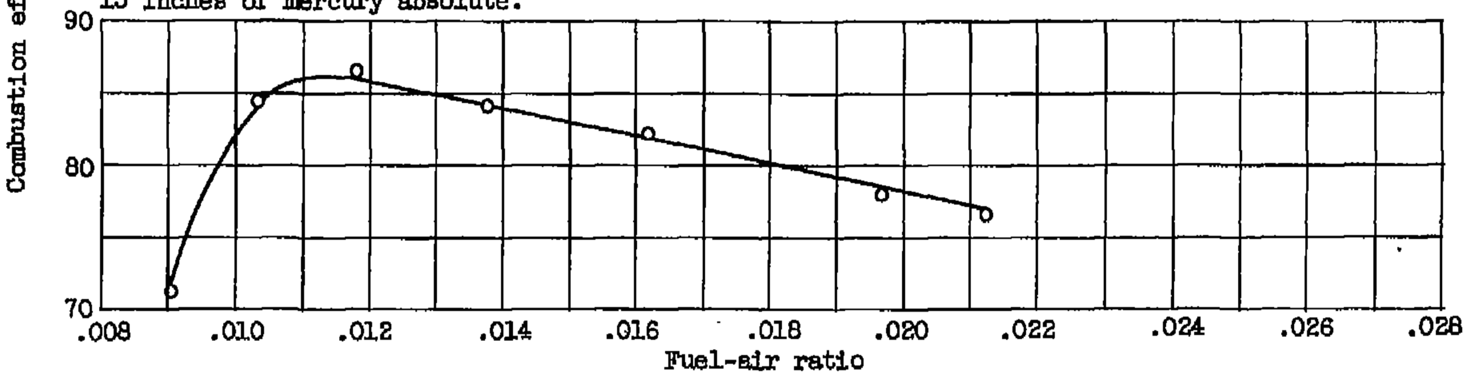



(b) Condition B. Air-flow rate, 1.49 pounds per second per square foot; inlet-air total pressure, 8 inches of mercury absolute.

Figure 4. - Combustion efficiency of experimental combustor configuration I. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.

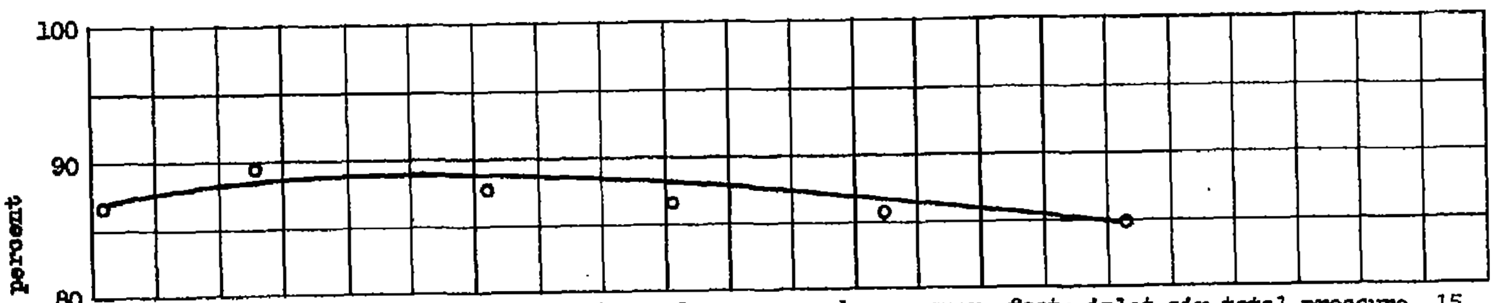



(c) Condition C. Air-flow rate, 2.14 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

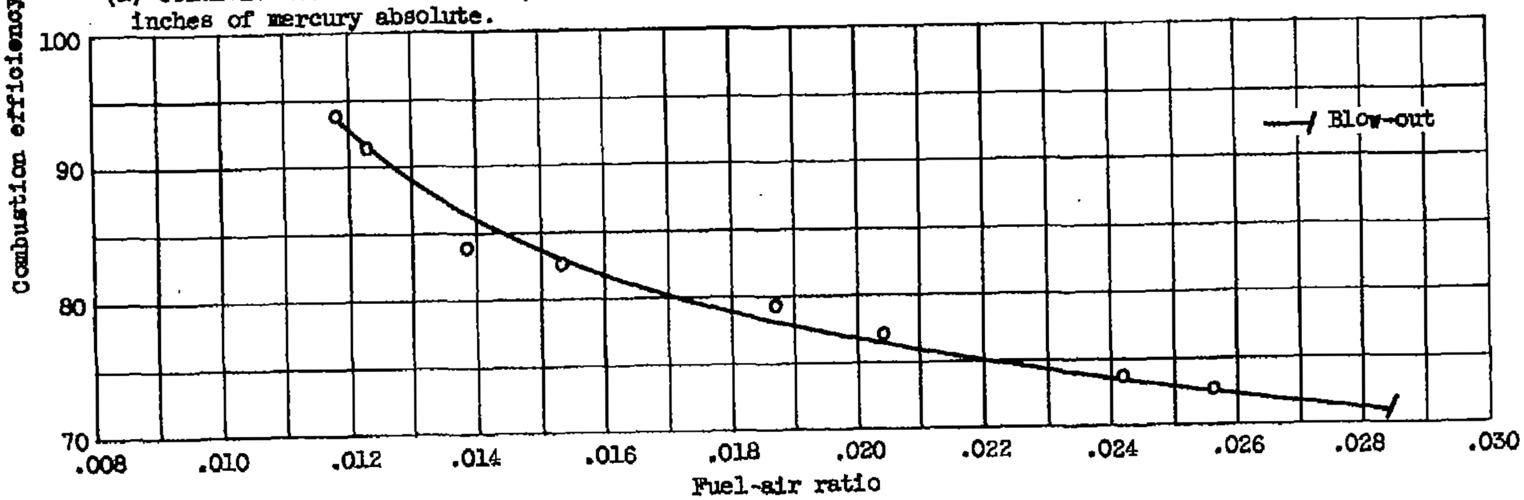



(d) Condition D. Air-flow rate, 3.62 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

Figure 4. - Concluded. Combustion efficiency of experimental combustor configuration I. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.

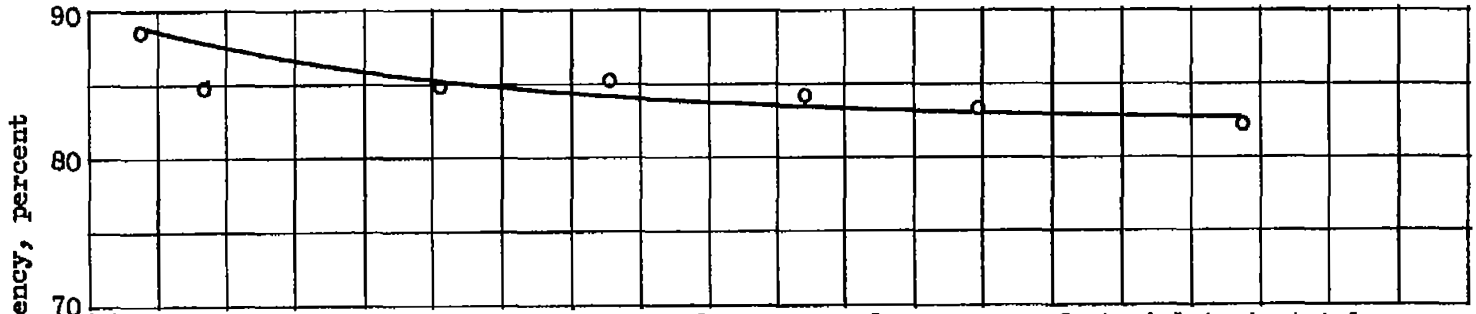



(a) Condition A. Air-flow rate, 2.78 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.




(b) Condition B. Air-flow rate, 1.49 pounds per second per square foot; inlet-air total pressure, 8 inches of mercury absolute.

Figure 5. - Combustion efficiency of experimental combustor configuration II. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.




(c) Condition C. Air-flow rate, 2.14 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

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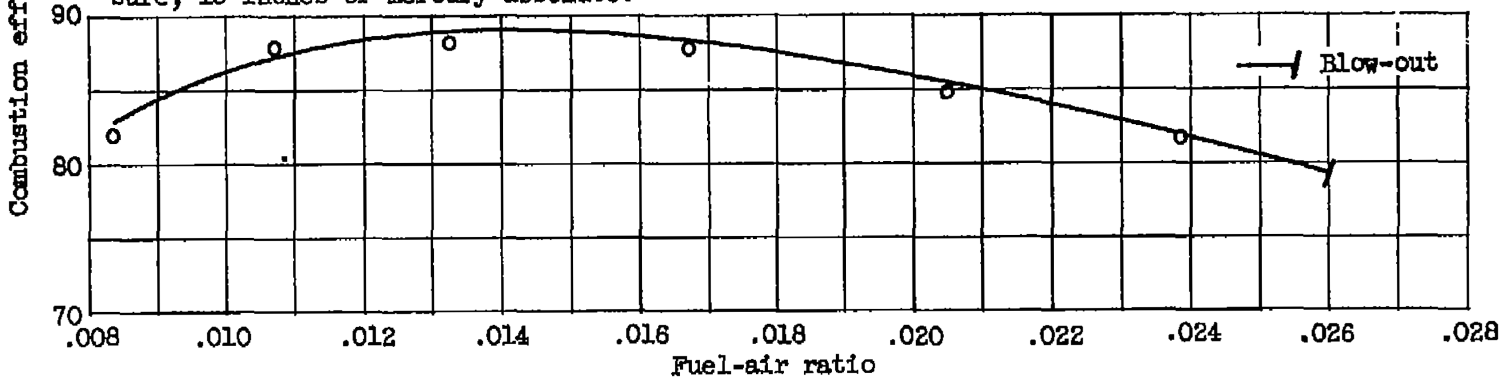


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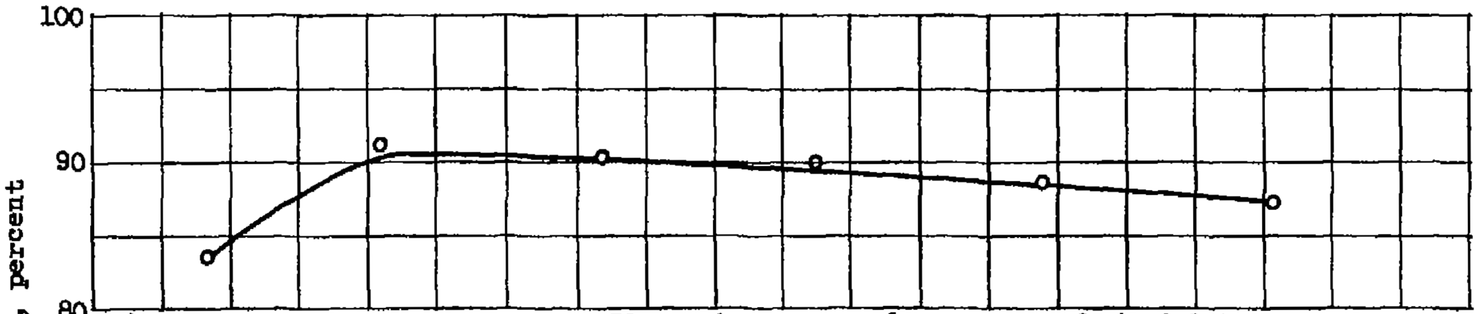
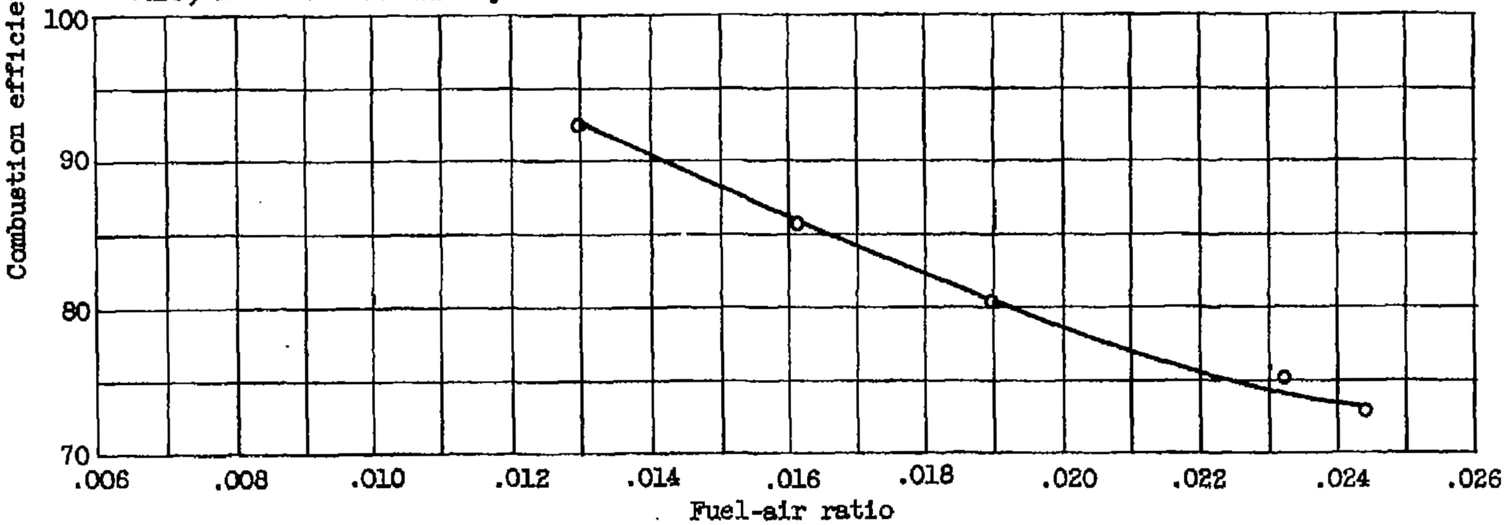
(d) Condition D. Air-flow rate, 3.62 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

Figure 5. - Concluded. Combustion efficiency of experimental combustor configuration II. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.

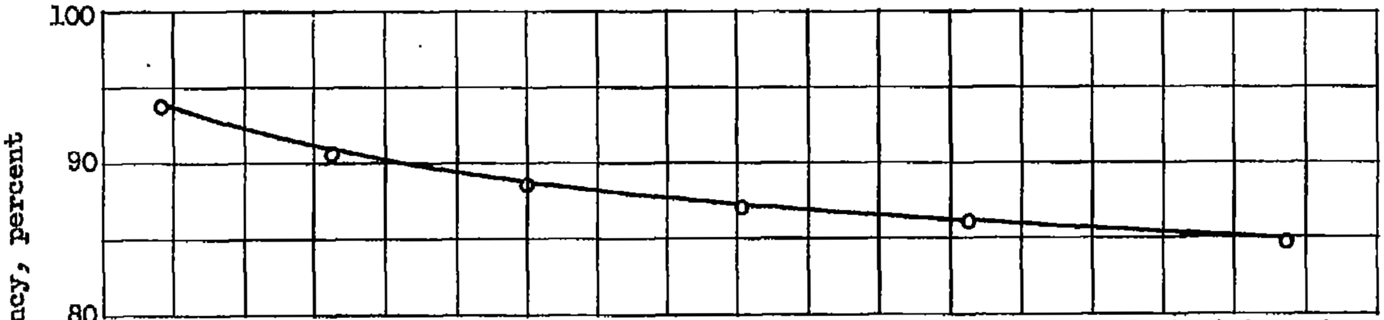



(a) Condition A. Air-flow rate, 2.78 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

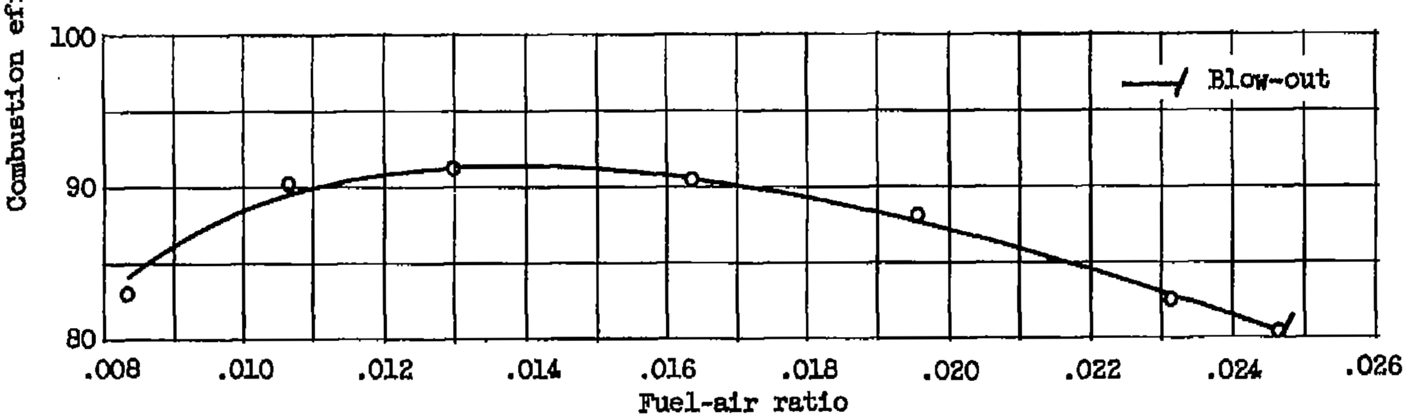



(b) Condition B. Air-flow rate, 1.49 pounds per second per square foot; inlet-air total pressure, 8 inches of mercury absolute.

Figure 6. - Combustion efficiency of experimental combustor configuration III. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.

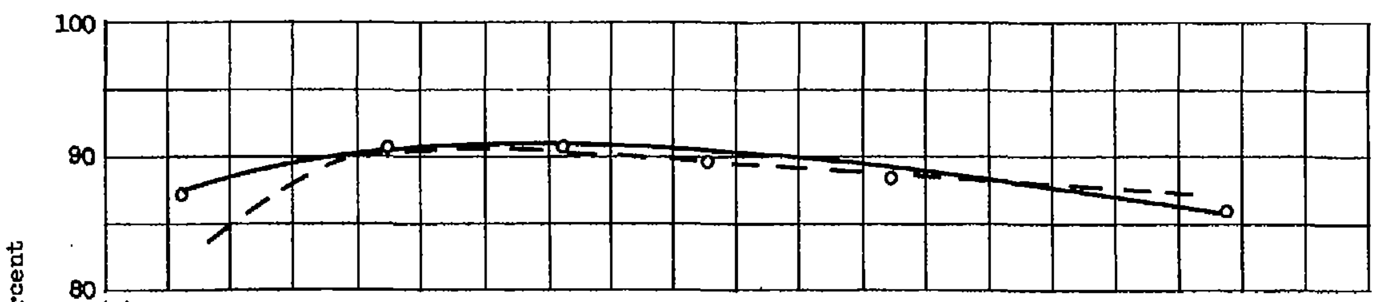



(c) Condition C. Air-flow rate, 2.14 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

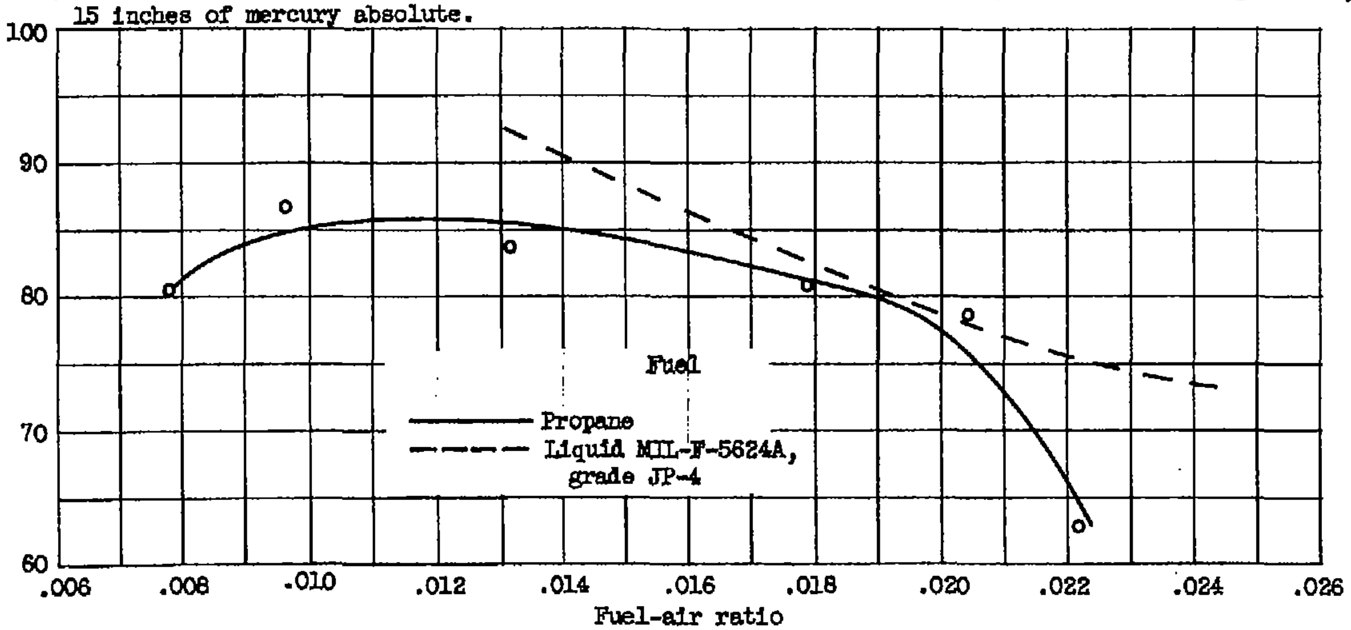



(d) Condition D. Air-flow rate, 3.62 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

Figure 6. - Concluded. Combustion efficiency of experimental combustor configuration III. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.

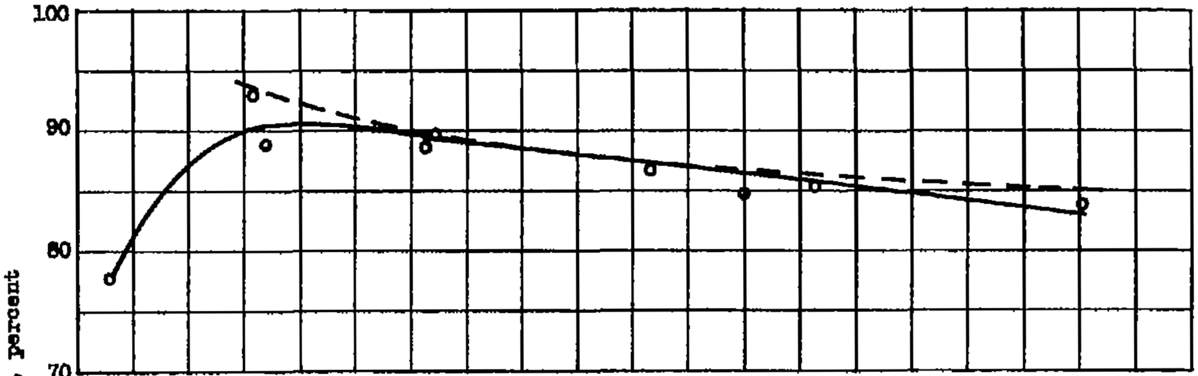



(a) Condition A. Air-flow rate, 2.78 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

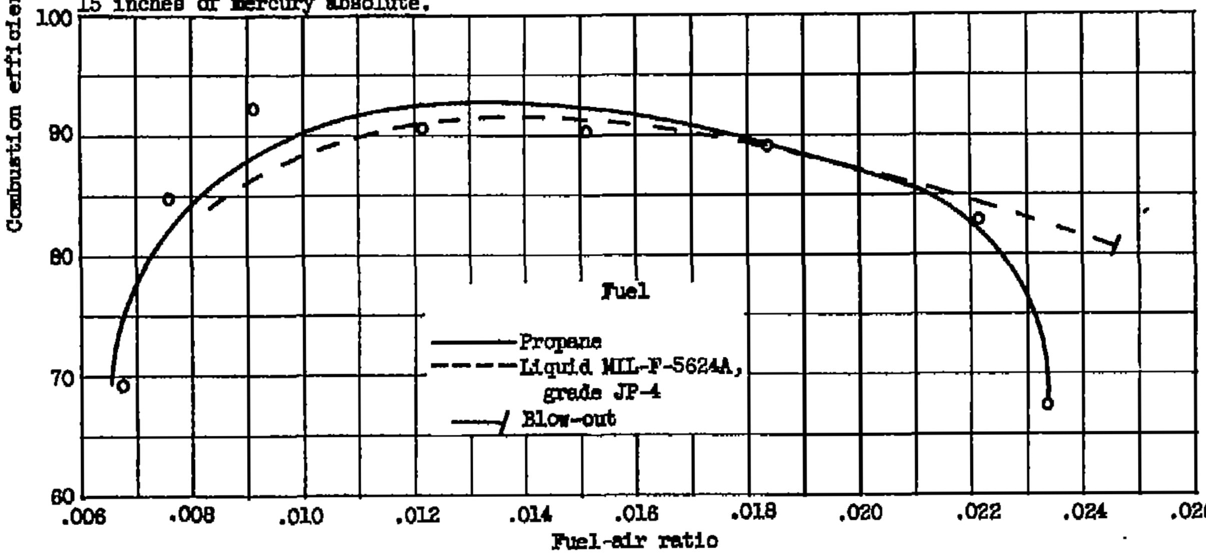



(b) Condition B. Air-flow rate, 1.49 pounds per second per square foot; inlet-air total pressure, 8 inches of mercury absolute.

Figure 7. - Combustion efficiency of experimental combustor configuration III with liquid and gaseous fuel. Inlet-air temperature, 268° F.




(c) Condition C. Air-flow rate, 2.14 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.




(d) Condition D. Air-flow rate, 3.62 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

Figure 7. - Concluded. Combustion efficiency of experimental combustor configuration III with liquid and gaseous fuel. Inlet-air temperature, 268° F.

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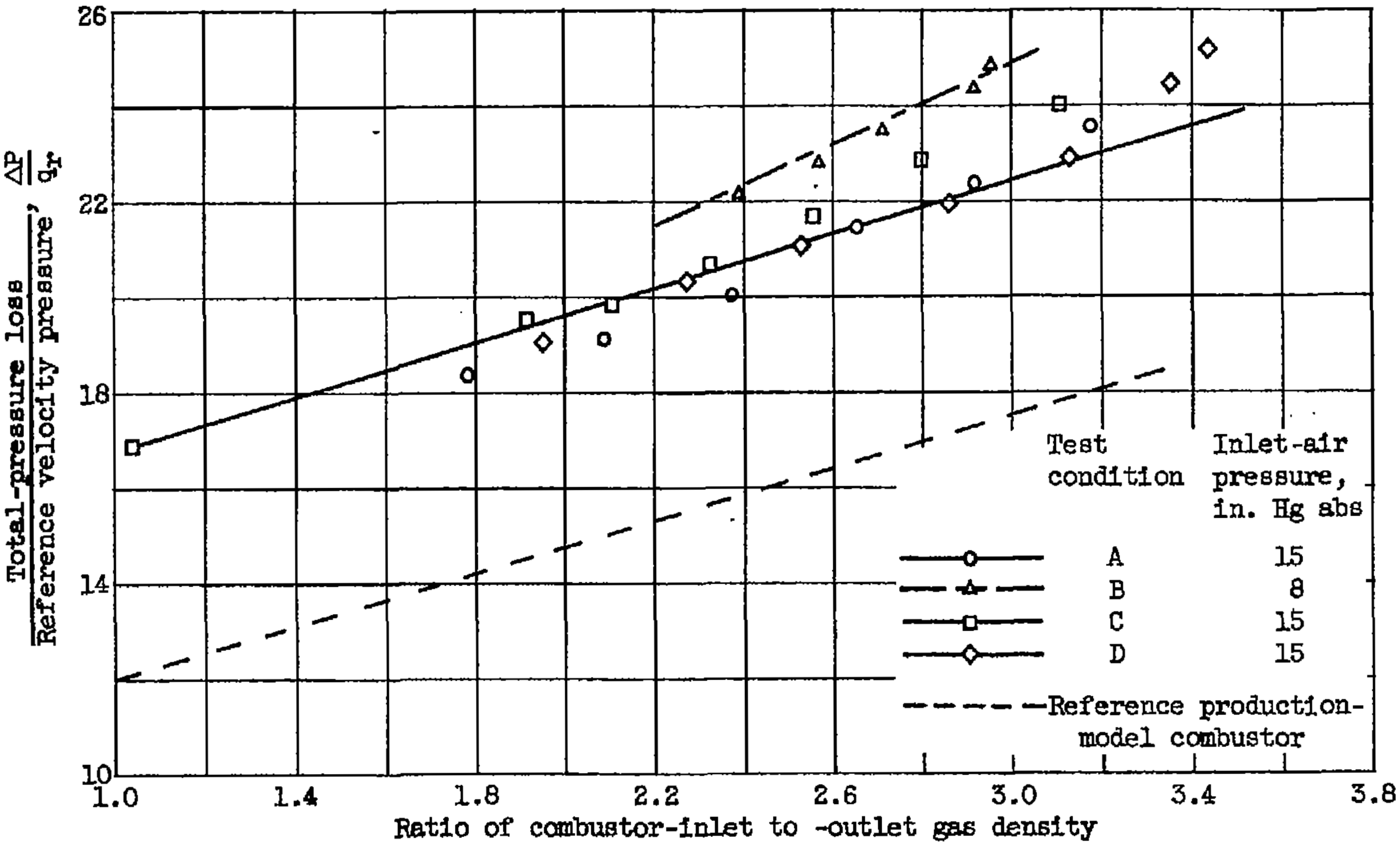
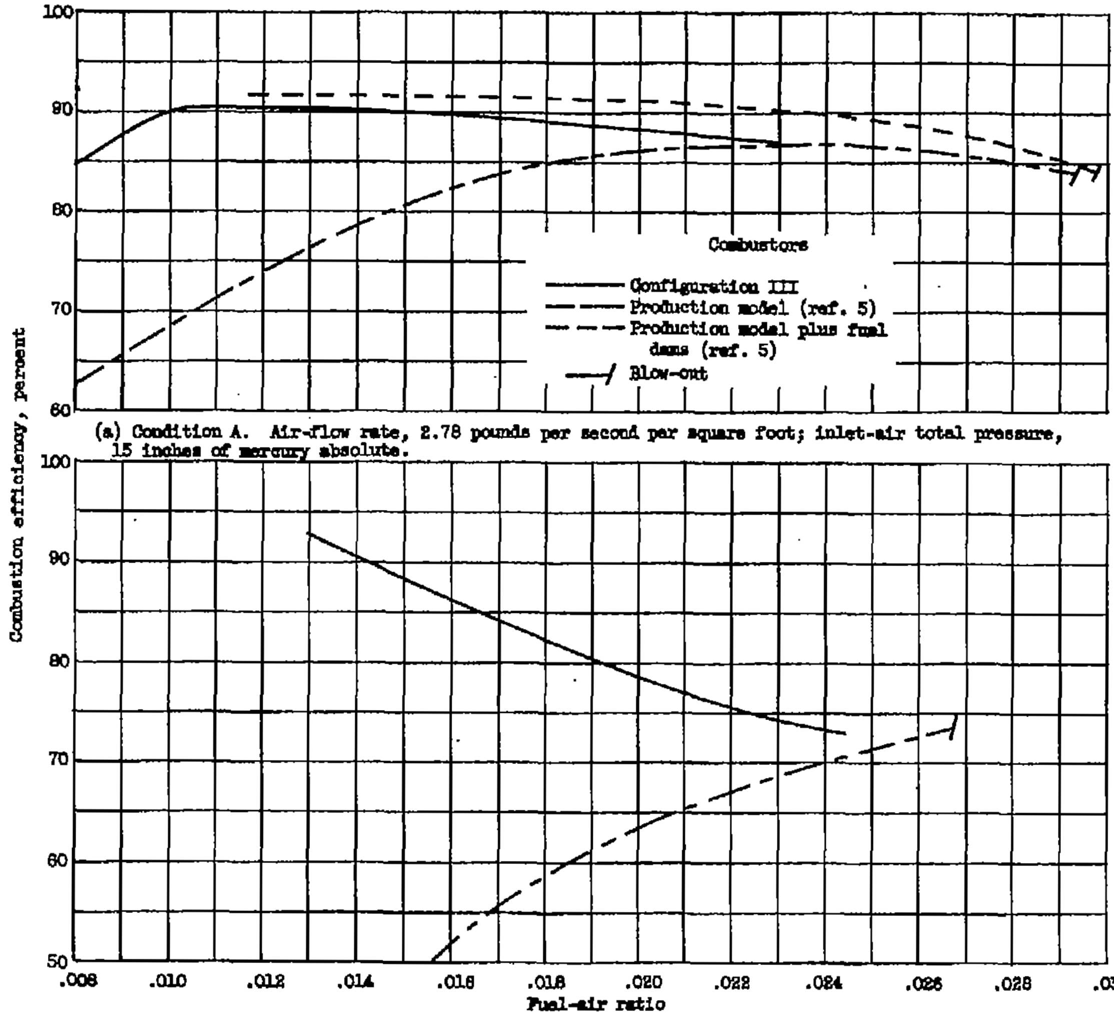


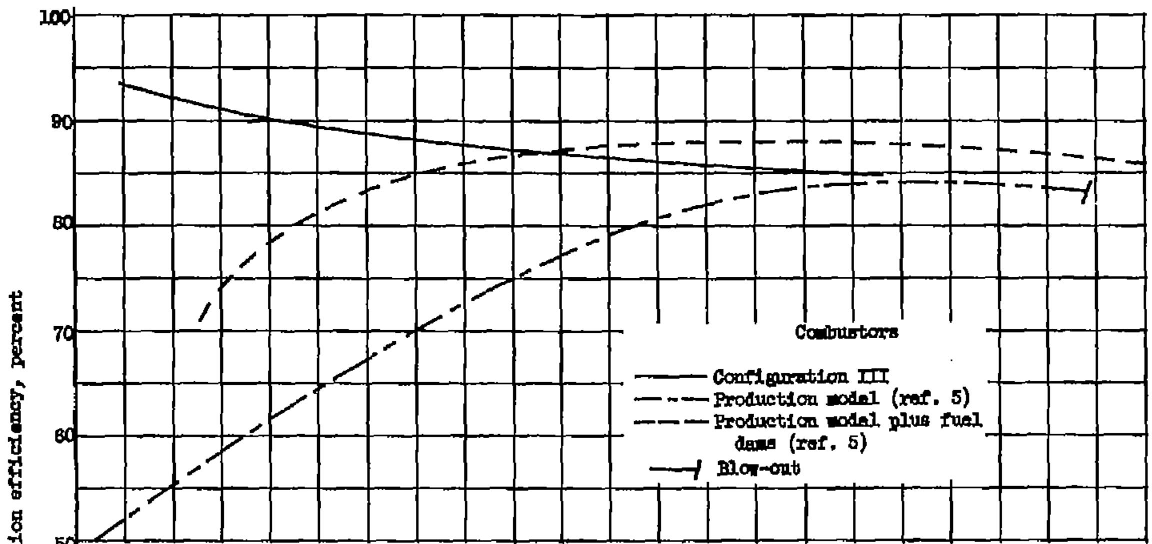

Figure 8. - Comparison of total-pressure losses of experimental combustor configuration III and production-model combustor. Inlet-air temperature, 268° F; fuel, MIL-F-5624A, grade JP-4.



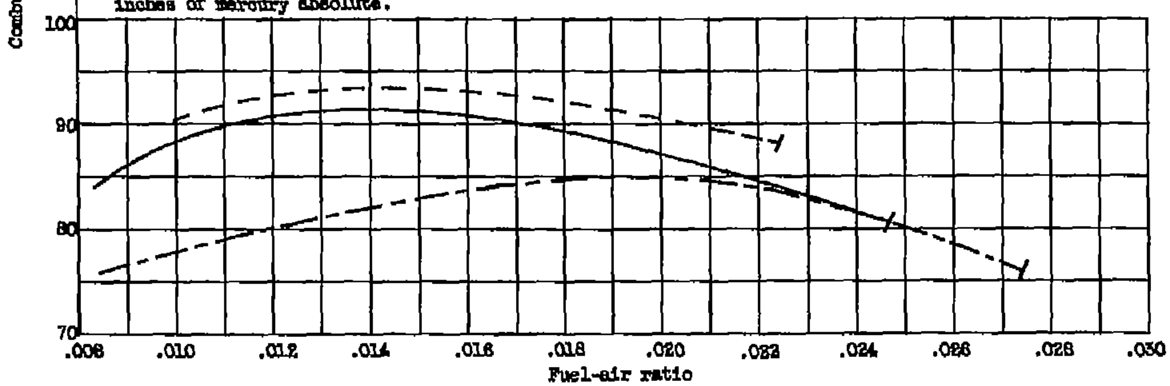

(a) Condition A. Air-flow rate, 2.78 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

(b) Condition B. Air-flow rate, 1.49 pounds per second per square foot; inlet-air total pressure, 8 inches of mercury absolute.

Figure 9. - Comparison of combustion efficiencies of experimental and production-model combustors. Inlet-air temperature, 288° F; fuel, MIL-F-5624A, grade JP-4.




(c) Condition C. Air-flow rate, 2.14 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.




(d) Condition D. Air-flow rate, 3.62 pounds per second per square foot; inlet-air total pressure, 15 inches of mercury absolute.

Figure 9. - Concluded. Comparison of combustion efficiencies of experimental and production-model combustors. Inlet-air temperature, 288° F; fuel, MIL-F-5624A, grade JP-4.

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